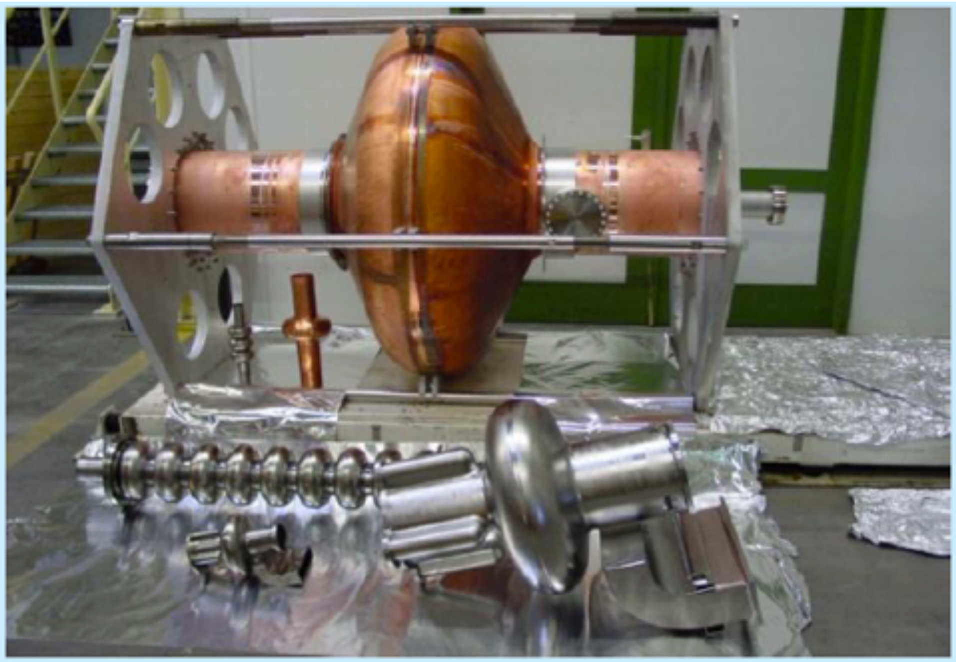
Surface chemistry and the quality factor of superconducting radio frequency (SRF) cavities

A. Romanenko

Outline

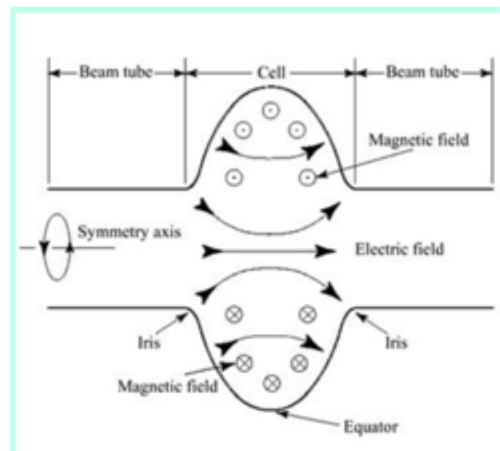
- SRF cavities
- Cavity quality factor
- Hydrofluoric acid “nanostripping”
- Practical recipe to increase Q_0

Superconducting RF cavities



SRF high beta cavities of different frequencies

ILC 9-cell elliptical cavity



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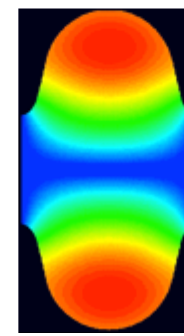

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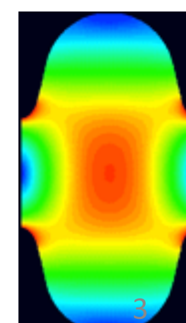
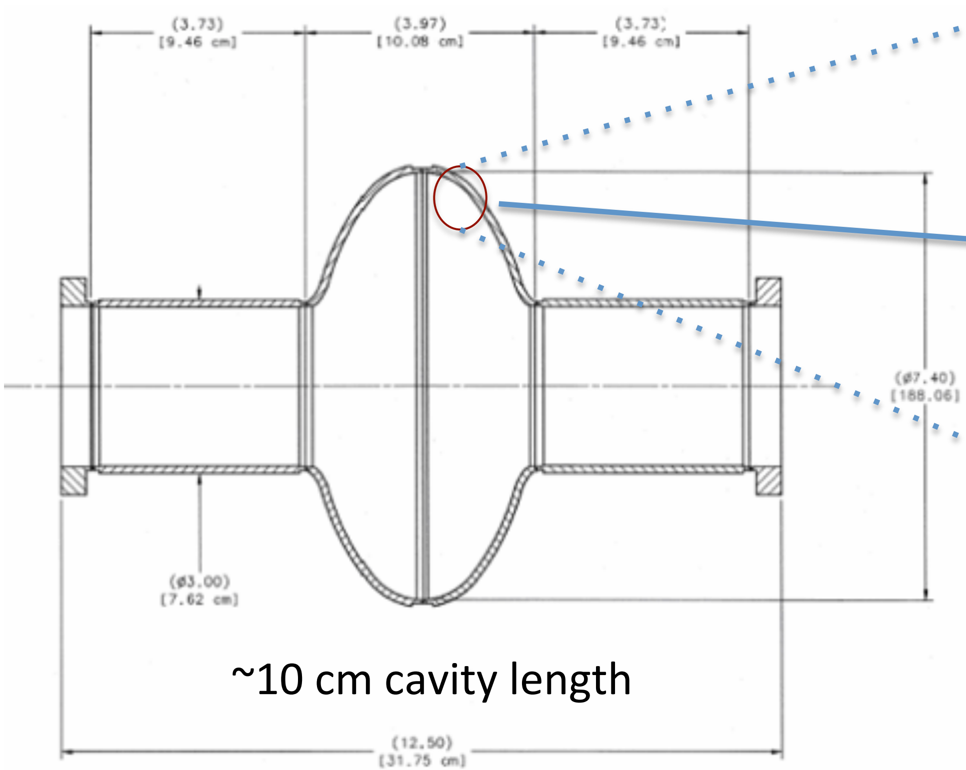
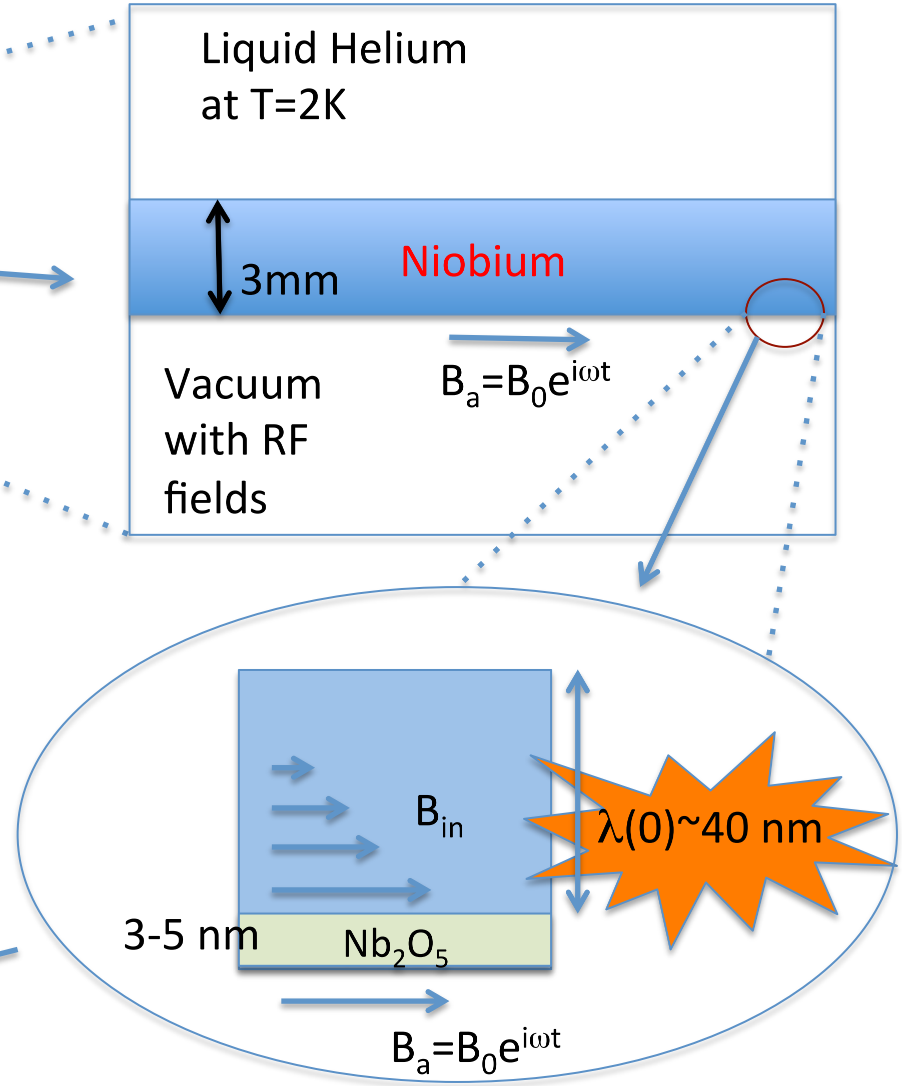


Technology of choice for: ILC, Project X, Cornell ERL, CEBAF, XFEL, SNS and many other accelerators

TM_{010} mode

Why (only) surface matters

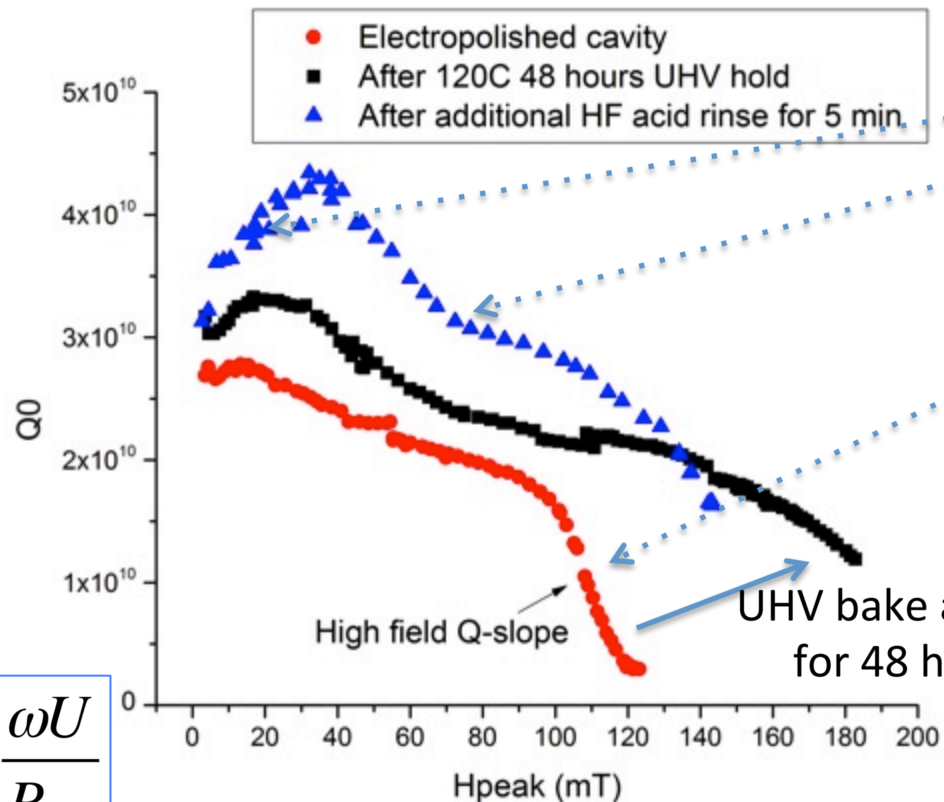




Inner wall surface nanostructure within λ~40nm completely determines surface resistance R_s~$1/Q_0$ of the cavity

Cavity quality factor

Understanding the shape of the Q(H) curve and learning how to control it – main objectives of our research



UHV bake at 120C for 48 hours

$$Q_0 = \frac{\omega U}{P_{diss}}$$

1.3 GHz bulk niobium cavity

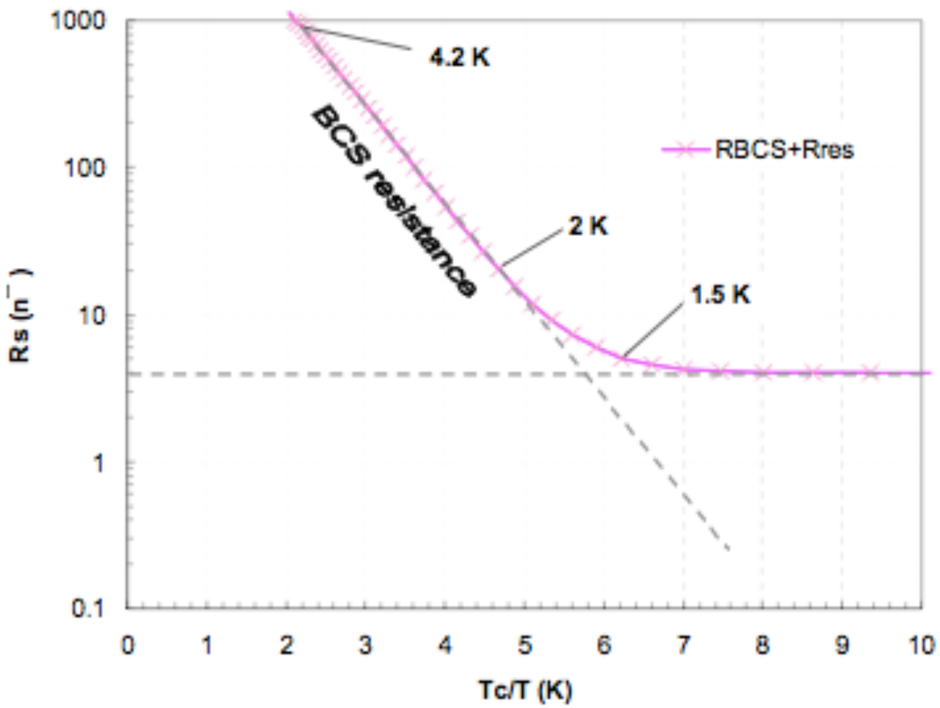
- Three distinct regions – **low**, **medium**, and **high** field Q-slope
- Respond differently to heat and chemical treatments
- The most dramatic effect - high field Q-slope removed by mild baking – UHV in situ annealing at 120C for 48 hours

Surface resistance

$$R_s = R_{BCS}(T) + R_{residual}$$

Residual normal electrons

Known and unknown contributions



Bauer- Review of surface resistance models

$$\boxed{Q_0 = \frac{\omega U}{P_{diss}} \propto \frac{1}{R_s}}$$

To increase Q_0:
Minimize all contributions to surface resistance at a required gradient

Need to know what and where in the surface ~40 nm all the contributors are!

Different ways to explore

① Detailed studies of the near-surface material structure (only first ~40 nm matter!) and superconducting properties by relevant state-of-the-art techniques - then apply the knowledge to the cavities

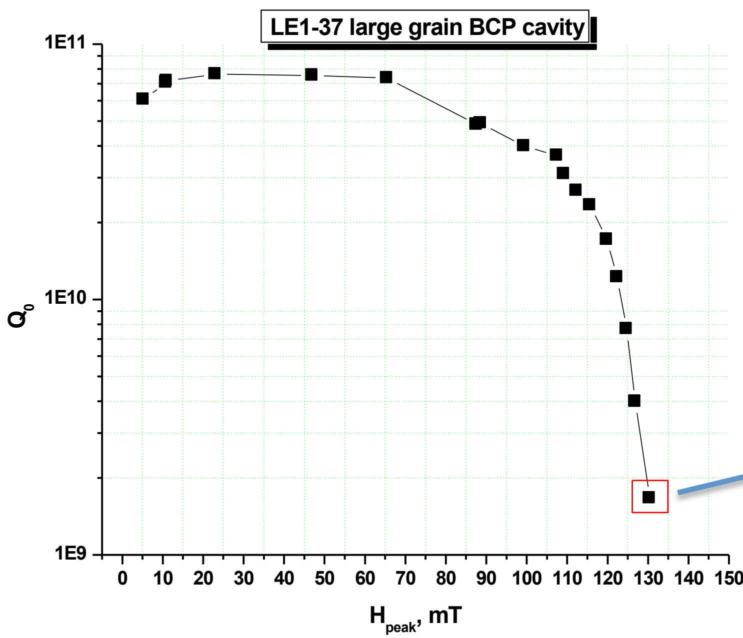
– DOE Early Career Award (A. Romanenko)

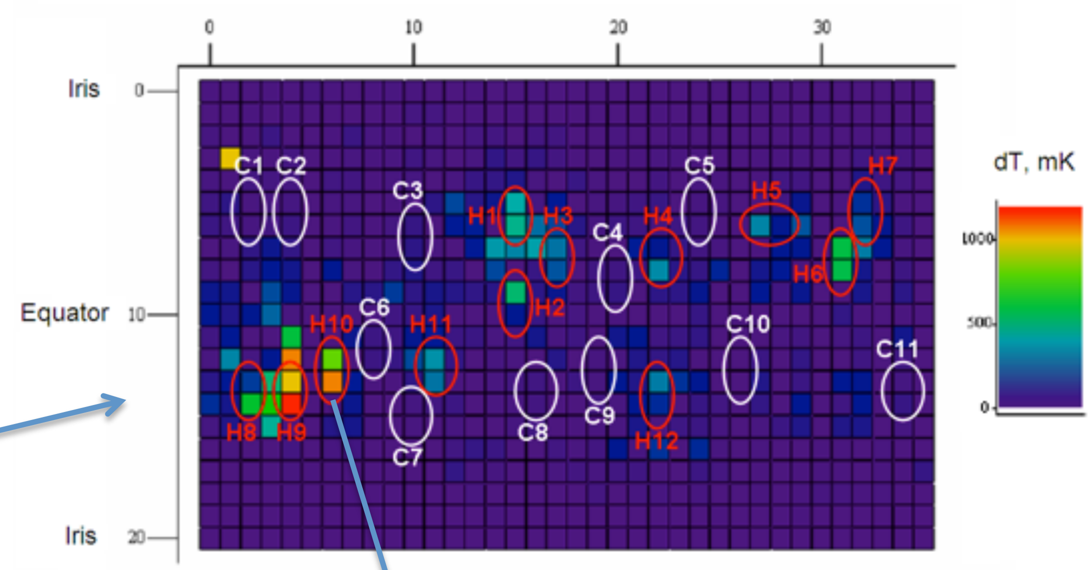
② Cavity experiments

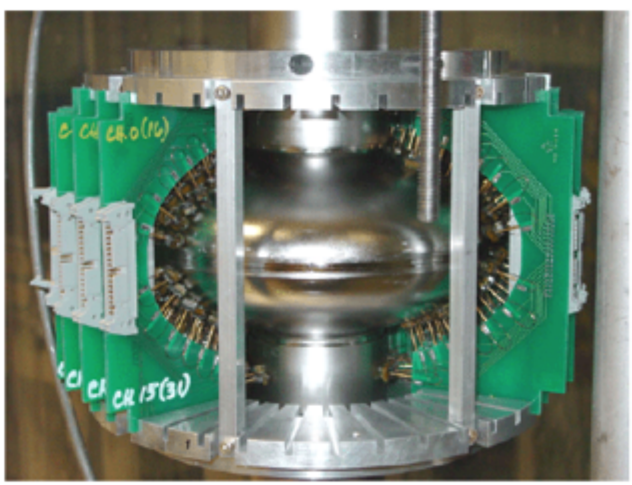
– Perform some new treatment/see what happens

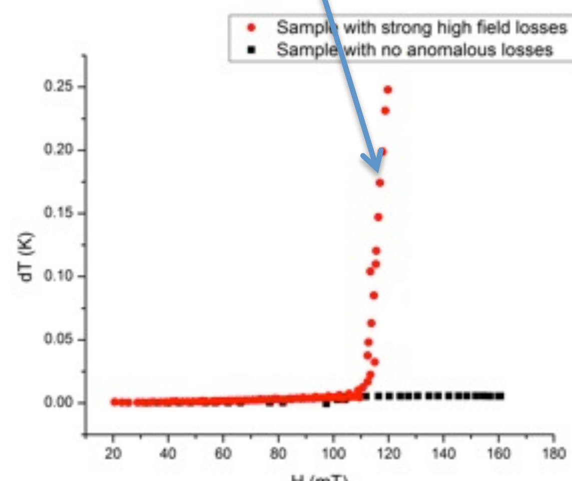
- Further progress in the detailed surface understanding is crucial – what to do with the surface and why? What do we need to achieve?

Best approach - thermometry and cutout



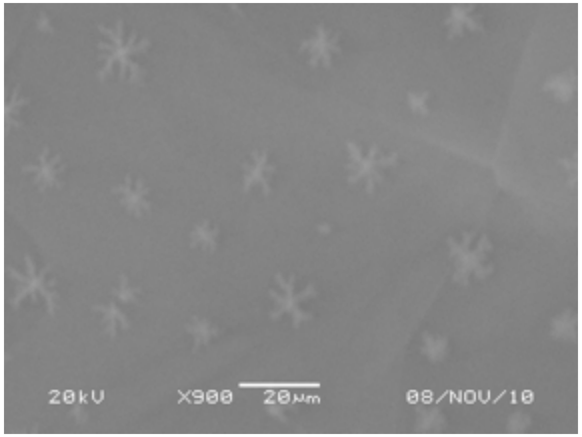


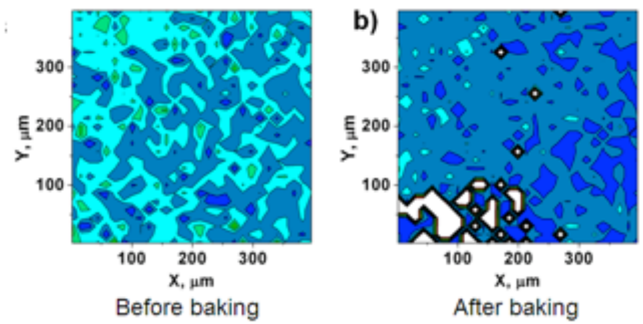


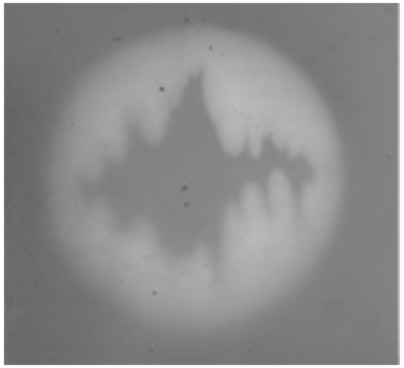


Detailed surface studies

- SEM/EDS, XPS
- Laser confocal scanning microscopy
- Elastic Recoil Detection for hydrogen profiling
- Positron annihilation studies – vacancy depth profiling
- Electron Backscattered Diffraction – dislocation density mapping
- FIB preparation of cross-sectional samples for defect structure observation in TEM and EELS analysis
- Local magnetization using single and arrays of microHall probes
- Magneto optical imaging
- Muon spin rotation
  - Bulk (TRIUMF)
  - Surface (Paul Scherer Institute)





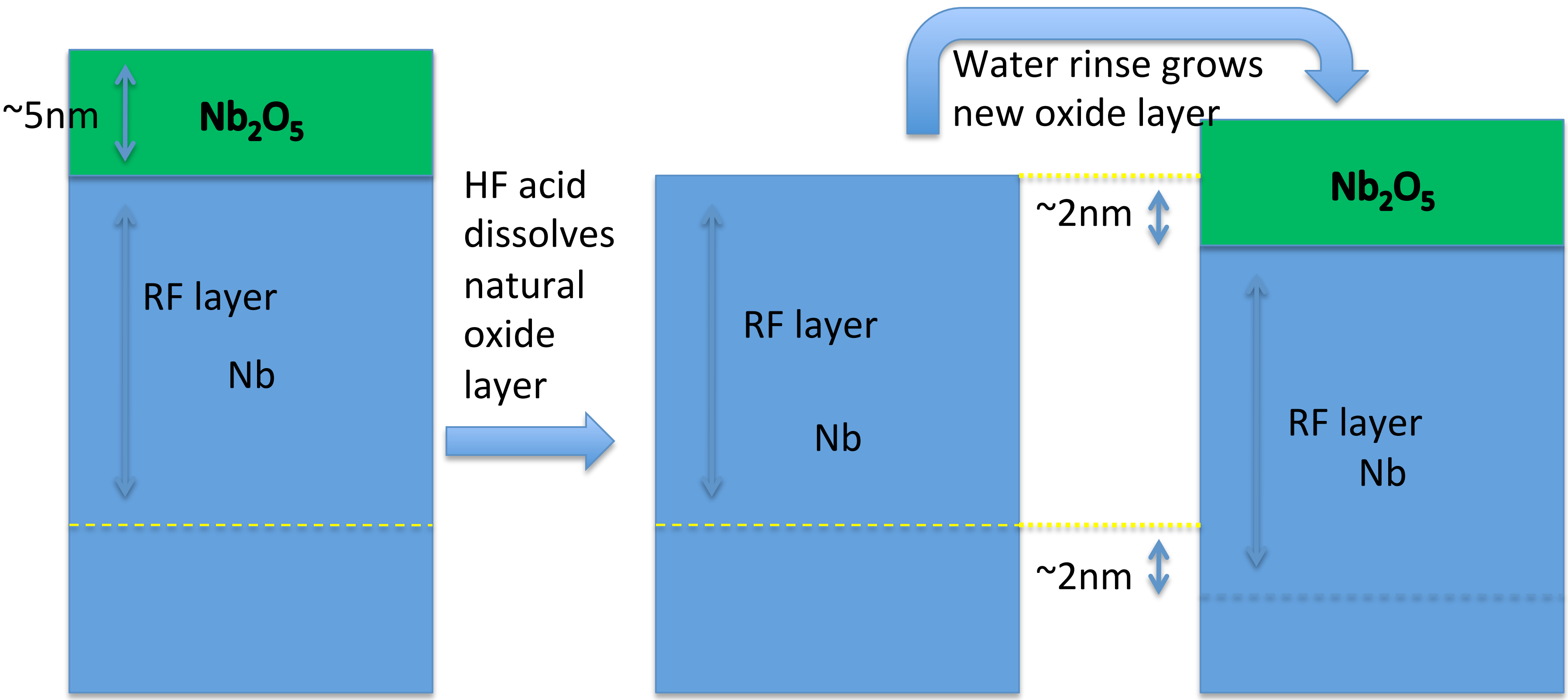


Beyond the scope of this presentation

Cavity "HF rinsing" experiments

- Purpose: explore the distribution of losses within the RF layer (~40 nm)
- Means:
  - Hydrofluoric acid rinsing as a "nanostripping" method - ~2 nm/step
  - Cavity Q(H) measurements after each HF rinse

Hydrofluoric acid rinse – "nanostripping"



Each HF/water rinse step consumes about 2 nm of niobium from the top of the RF layer determining the surface resistance and moves deeper into the bulk – depth profiling of the losses is possible

HF rinse procedure

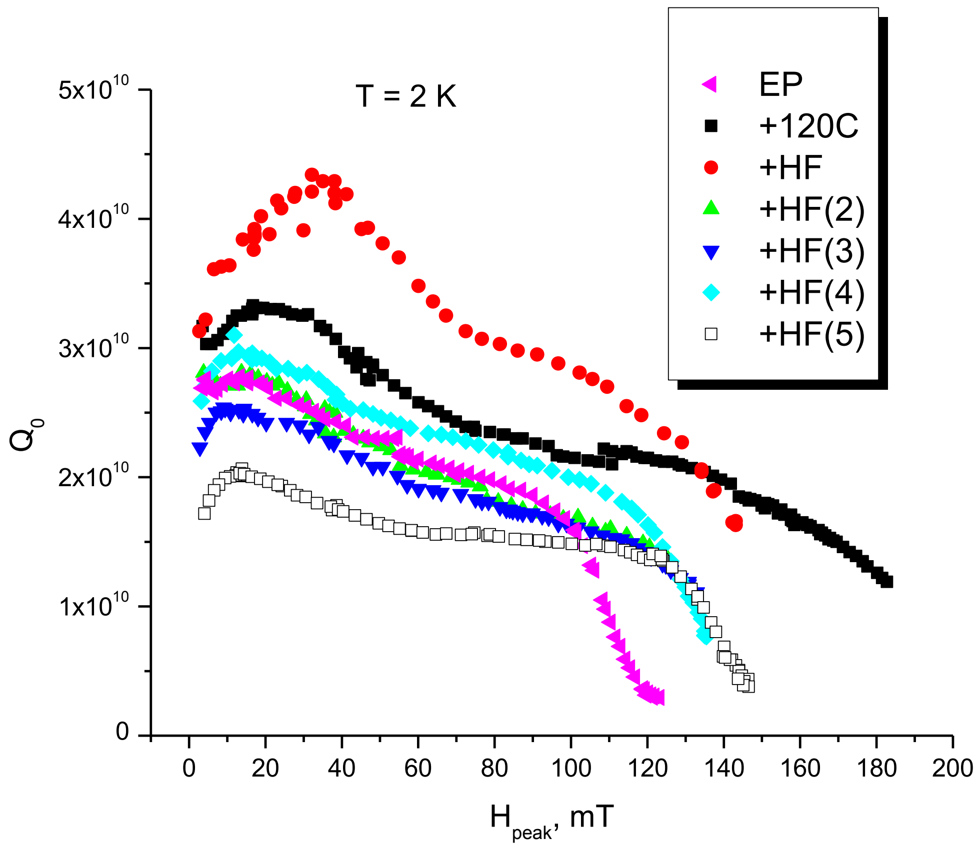
Filling with HF

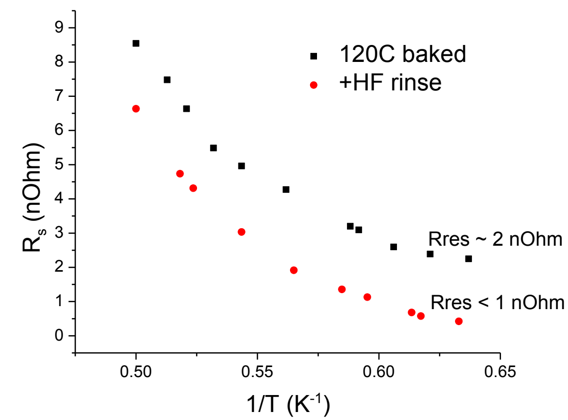
5 minutes hold

HF dumping

DI water rinse

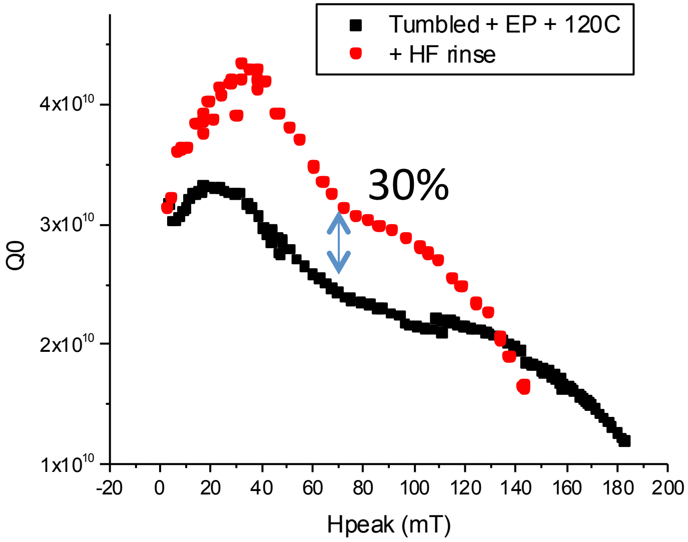
Results on EP fine grain (tumbled)

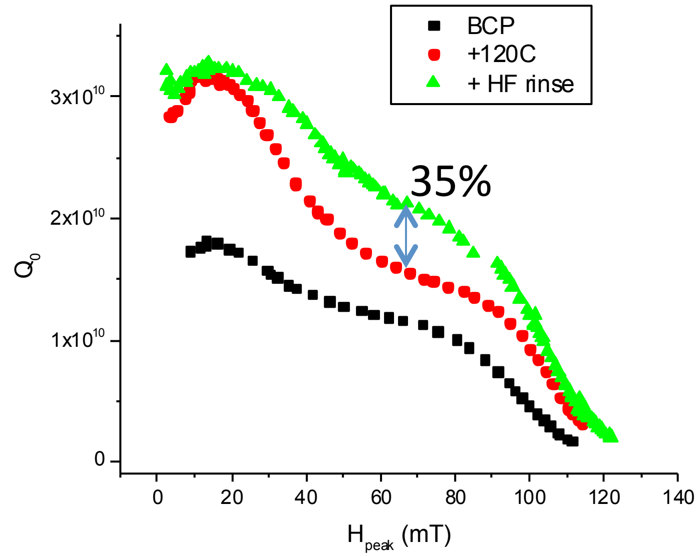


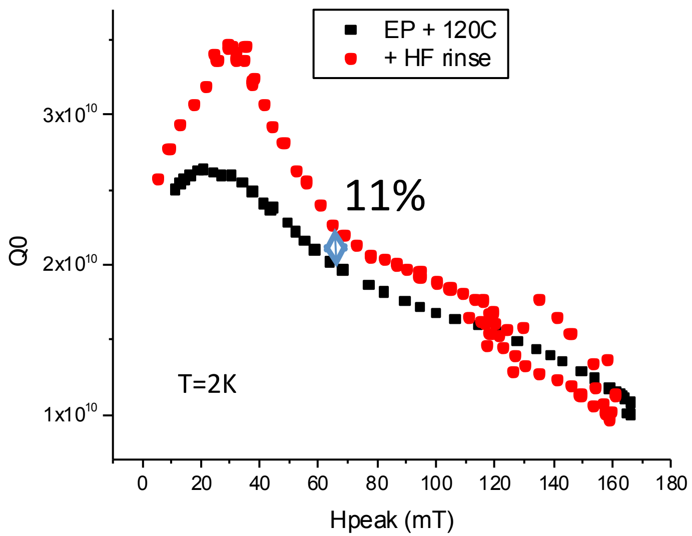


- ✓ Single HF rinse after mild baking significantly improves medium field Q0
- ✓ Multiple HF rinse cycles do bring the high field Q-slope back
- ✓ Onset field is still higher than before baking by ~25 mT after total 5 HF rinse cycles
  - ✓ Further rinses in queue

Simple higher Q_0 recipe



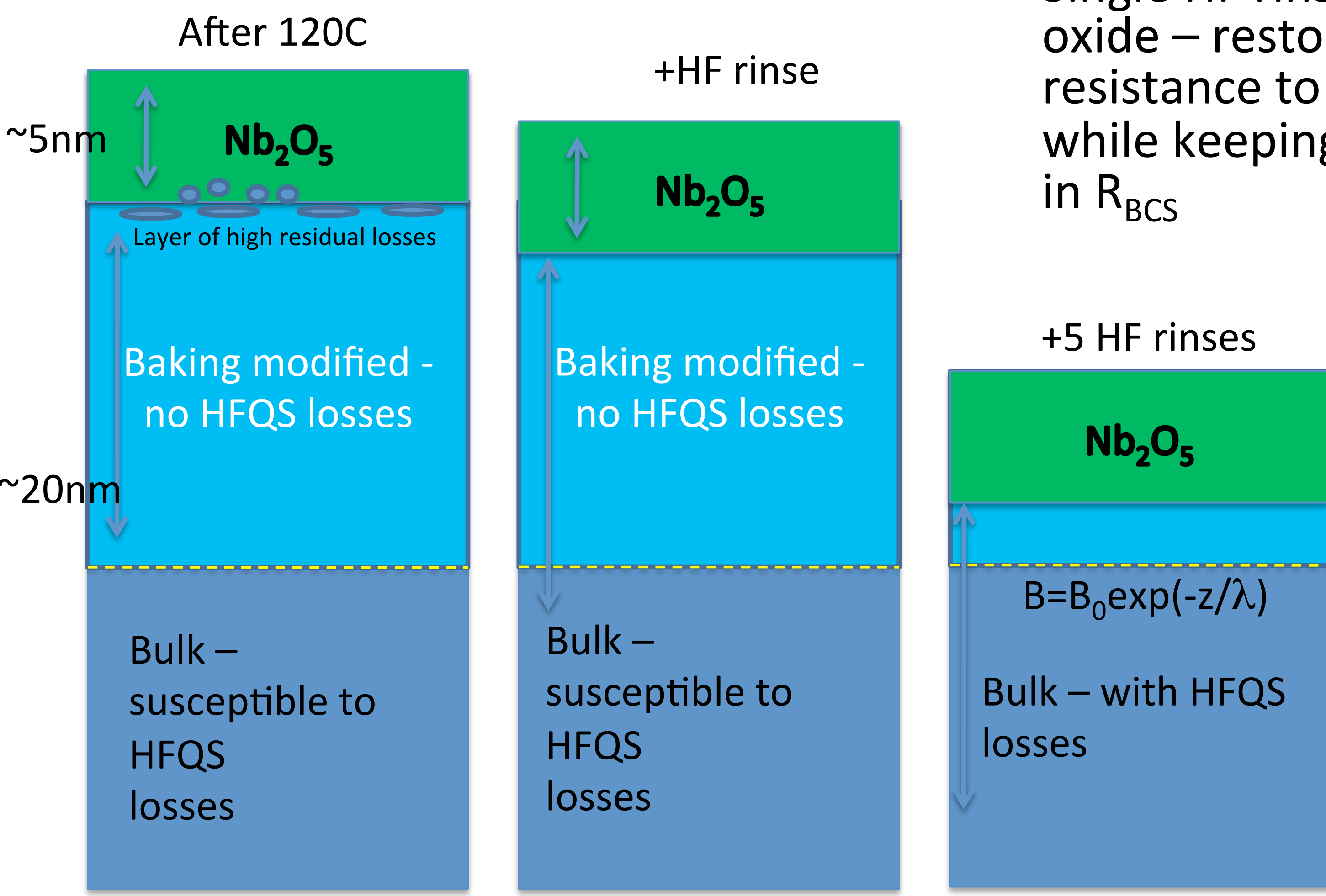




- FNAL single cell data -> single HF rinse (5 min) followed by water rinse is beneficial for the medium field Q value – gains of up to 35% measured at 70 mT

Possible interpretation

- Literature – 120C enhances residual resistance; possibly due to suboxide formation
- Single HF rinsing and regrowing oxide – restores residual resistance to pre-bake state while keeping the improvement in R_{BCS}



An estimate of the remaining thickness from the HFQS onset:

125 mT * exp $(-h/\lambda)$ = 100 mT => h~8nm

Conclusion

- HF "stripping" studies provide a possible cheap way to raise the Q_0 of niobium cavities
- Recommendation: perform HF rinse as a last step before high pressure water rinsing for cavities targeted for CW projects